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LATE JURASSIC TO LATE CRETACEOUS DEVELOPMENT OF ISLAND ARC CRUST IN SOUTHWESTERN PUERTO RICO.

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ABSTRACT

Based on fossil assemblages, radiometric ages, and rock and mineral chemistry, three stages can be distinguished in the development of the island arc crust in southwest Puerto Rico. Records of the first and second stage are preserved in the cherts and metamorphic rocks of the Bermeja Complex. The third stage is represented by the volcanic and sedimentary rocks, that unconformably overlie the Bermeja Complex, and by the intrusive rocks, associated with the volcanics. Radiolarian assemblages suggest three chert forming periods: 1) Kimmeridgian - Tithonian, with northern Tethyan to Boreal paleogeographic origin, deposited at abyssal depths; 2) Hauterivian - Aptian, deposited at bathyal depths; and 3) Cenomanian to Campanian in the Tethyan Realm. The basaltic rocks of the Bermeja Complex range in metamorphic grade from weakly metamorphosed prehnite - bearing rocks, through greenstones, to amphibolites. Although the whole rock geochemistry is not conclusive, the major, trace, and REE data for the higher grade metamorphic rocks suggest a possible ocean floor origin, whereas the lower grade grade metamorphics may have originated in an island arc setting. Clinopyroxene compositions for the low grade rocks (greenstones, dikes, and two pyroxene gabbro) confirm an island arc origin. Radiometric ages indicate a magmatic and metamorphic event in the Early Cretaceous corresponding to the second chert forming period, whereas the third chert forming period is coeval with the radiometric age for the intrusion of the Maguayo Porphyry diorite, and resetting of the metamorphic ages. Volcanics associated with the intrusions were probably subaerial and are partly covered by Santonian and Campanian reef and shelf limestones.

INTRODUCTION

Puerto Rico, the easternmost island of the Greater Antilles is located at the northern margin of the Caribbean Plate. The island consists of a deformed core of volcanic, volcaniclastic, and sedimentary rocks of Late Jurassic to Early Tertiary age, which was intruded in the Late Cretaceous and Early Tertiary by felsic plutons. This core, which extends in an east-west direction across the center of the island, is overlain on the north and south coasts by slightly tilted Oligocene and younger sedimentary rocks and sediments (Fig.1) (Briggs and Akers, 1965, Mattson, 1966). The southwestern part of the island consists of three linear belts of serpentinite separated by rocks of Late Cretaceous age, which are locally overlain by younger sedimentary rocks and sediments. The serpentinite, with rafts of amphibolites, greenstones, and cherts, belongs to the Bermeja Complex, which represents the oldest dated rocks on Puerto Rico. Previous workers (eg. Mattson, 1973, Mattson and Pessagno, 1974, 1979, Wadge and others, 1983) have regarded the Bermeja Complex as representing a dismembered ophiolite complex. However, the evidence is ambiguous and it could also represent island arc basement. Based on petrology, geochemistry, and fossil and radiometric ages this study attempts to compile the geologic history of southwestern Puerto Rico.

BERMEJA COMPLEX

The Bermeja Complex (Fig. 1a) was first described by Mattson (1960), who distinguished four rock types: serpentinized peridotite (Mattson,

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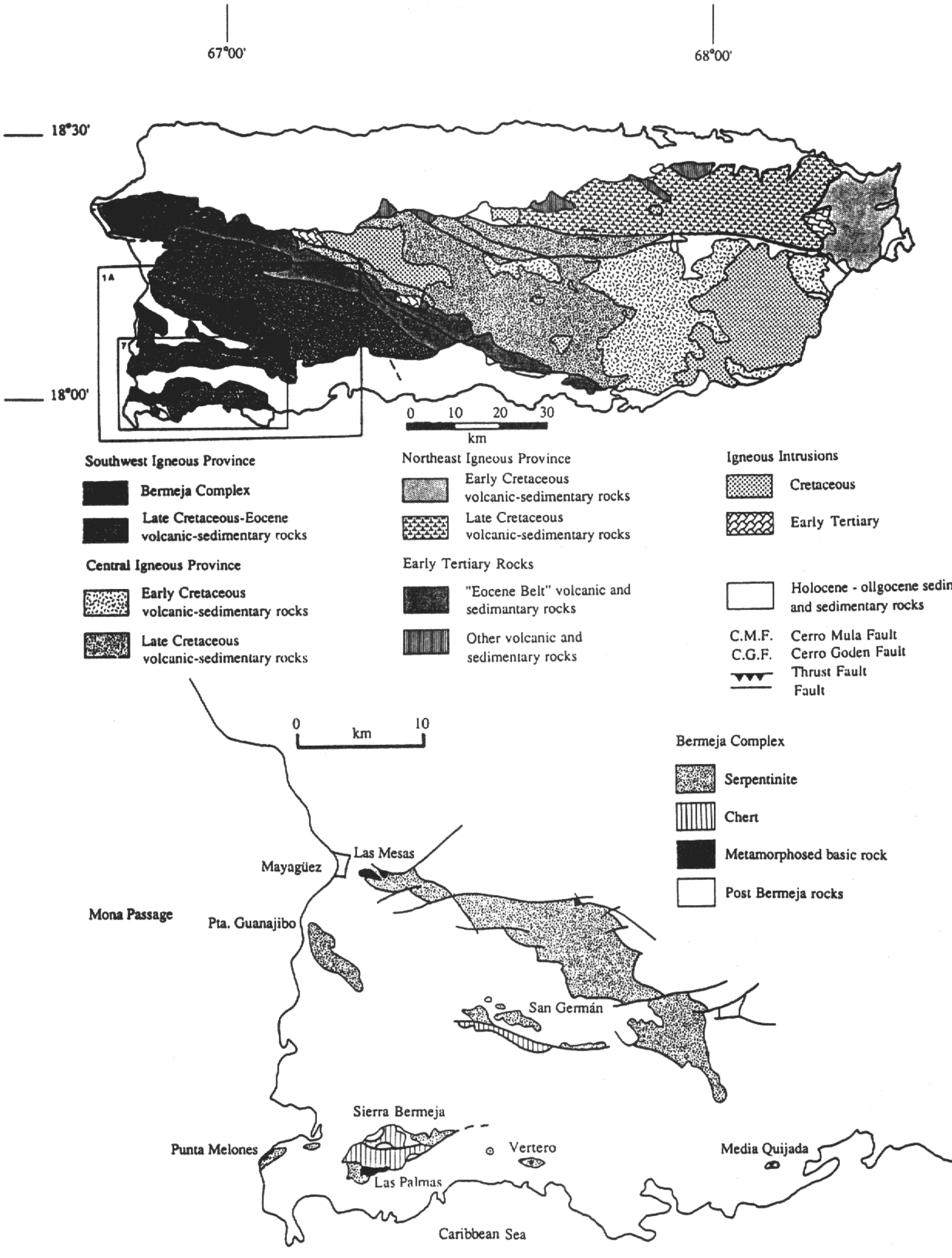

Fig.1: Geologic map of Puerto Rico. Insets: Figure 1A: Bermeja Complex, and figure 6: Maguayo Volcanic Center.

1960, 1964), spilite (here named the Las Mesas Greenstone), amphibolite (later named the Las Palmas Hornblende Schist and Amphibolite; Mattson, 1973), and silicified volcanic rock and/or chert (later named the Mariquita Chert by Mattson, 1973).

Of the three serpentinite belts, the northern one consists predominantly of serpentinite, and extends from the city of Mayaguez, ESE towards Sabana Grande (Mattson, 1960, McIntyrė, 1975, Curet, 1986). Greenstone and amphibolite occurring within the serpentinite of this belt are exposed in two quarries just east of Mayaguez (Mattson, 1960, Curet, 1981, 1986). In the northern quarry, non-foliated greenstones comprise a bedded sequence, with beds from 20 cm to several meters in thickness, of basaltic flow rocks, volcaniclastic conglomerates and sandstones. In the southern quarry metamorphosed and veined volcaniclastic sandstones are associated with non-foliated amphibolite. About 3 Km. ESE of Maricao an outcrop of "amphibolite" -breccia in serpentinite was described by McIntyre (1975). A restudy of this outcrop has identified the "amphibolite" as a hornblende-two-pyroxene gabbro, with prehnite and hydrogrossular veining giving it a foliated impression.

The other two serpentinite belts are discontinuous. One runs from Punta Guanajibo, eastward through San German, where outcrops of Mariquita Chert occur (Volckmann, 1984c) to join the northern belt near Sabana Grande. (Mattson, 1960, Krushensky and Monroe, 1979, Volckmann, 1984c). Locally the serpentinite is cut by small basaltic and andesitic intrusions. The third, southernmost, belt extends from Punta Melones across the Sierra Bermeja (Fig. 1) (Mattson, 1960, 1973, Volckmann, 1984 b,d); east of the Sierra Bermeja, only a few patchy exposures of the Bermeja Complex are encountered at Cerro Vertero, (Volckmann, 1984b), and Media Quijada (Krushensky and Monroe, 1979). At both Punta Melones and Sierra Bermeja the serpentinite, which contains amphibolite blocks some of which are on the order of tens of meters in diameter (Mattson, 1960, Renz and Verspyck, 1962, Tobisch, 1968), is overlain by chert. In the largest amphibolite raft, near barrio Las Palmas, foliated amphibolites are cut by meta-basaltic dikes, which cross-cut the foliation, and they themselves may be off-set along small faults. The serpentinite of this southern belt is intruded by Late Cretaceous intrusions, the most prominent of which is the diorite stock of the Maguayo Porphyry.

Petrology of the metamorphosed rocks

The petrography of representative samples of the Bermeja Complex is summarized in Table 1. The amphibolites have a medium-grade metamorphic paragenesis of green hornblende and calcic plagioclase, sometimes with relics of clinopyroxene, brown hornblende, and plagioclase. Two varieties of amphibolite can be distinguished based on the texture: foliated and non-foliated, there is however no difference in mineralogy between the two varieties. Many of the amphibolites show evidence of retrograde metamorphism. In the southern serpentinite belt

Table 1: Petrography of representative samples of the Bermeja Complex.

No:	Location:	paragenesis + relics	retrograde minerals:
Foliated amphibolite			
VP1	Las Palmas	green hnbl.-plag.(labr.)-Qtz-sphene-magnetite	chlorite-calcite
VP3	Las Palmas	brown hnbl.cores-cpx.relics-green hnbl.-plag.-mgnt.	
VP4	Las Palmas	browngreen hnbl.-plag.-Qtz.-mgnt.	
VP85	Media Quijada	br.green hnbl.-plag.(labr.-bytw.)-cpx.relics	calcite
EC14	Punta Melones	green hnbl.-cpx.relics-sphene	prehnite
Non-foliated amphibolite			
VP66	vertedero Lajas	green hnbl.-plag.-sphene-cpx.relics	sericite
VP78	Punta Melones	green hnbl.-plag.-cpx.relics	serpentine?-sericite
VP80	Punta Melones	green hnbl.-plag.(olig.-and.)-sphene-cpx.relics	
VP180	Las Mesas	green hnbl.-plag.-cpx.relics	actinolite-chlorite-albite
Meta-basalt porphyry			
VP2	Las Palmas	actinolite-green hnbl.-plag.(alb.)	chlorite-Qtz.
VP117	Las Palmas	actinolite-green hnbl. plag.(alb.)-cpx.relics	
Greenstones			
EC13	Las Mesas	cpx-plag.(alb.)	calcite-chlorite-prehnite-epidote
Two pyroxene gabbro			
VP179	Maricao	brown hnbl.-cpx-opx-plag.(bytw.)	prehnite-chlorite-hydrogrossular

this is evidenced by the presence of chlorite. The amphibolites from the northern belt, associated with the greenstones (eg. VP180) contain actinolite, chlorite, and albite, indicating they were probably remetamorphosed during the greenschist metamorphism. The meta-basalt porphyry dikes in the Las Palmas area, are metamorphosed to a low grade metamorphic facies with a paragenesis of actinolite, green hornblende, and albite, sometimes with clinopyroxene relics preserved. The greenstones of the northern serpentinite belt are composed of clinopyroxene and plagioclase, the latter is often albitized, together with veins of epidote, chlorite, and prehnite. The gabbro near Maricao (VP179) consists of clinopyroxene, orthopyroxene, and calcic plagioclase. The pyroxenes are rimmed by brown hornblende, of a composition falling in the pyroxene miscibility gap, on the tie-line between the orthopyroxene and clinopyroxene, suggesting the amphibole to be of late magmatic origin. Secondary chlorite and prehnite, and thin, parallel prehnite and hydrogrossular veins indicate a very low-grade metamorphism.

Whole rock geochemistry

Fourteen new major and trace element analyses (obtained by X-ray fluorescence at Mich. Tech. Univ., Rose and others, 1986) for the basic rocks of the Bermeja Complex are presented in Table 2. In order to try and determine the tectonic environment of the rocks of the Bermeja Complex immobile trace elements were plotted on discriminant diagrams (Fig. 2). The Ti vs Zr, and the Cr vs Y (Pearce, 1982) , and the log (Zr/Y) vs log Zr diagrams (Pearce and Norry, 1979) show most analyses clustering in the Mid Ocean Ridge Basalt (MORB) field. The lower grade metamorphic basaltic rocks fall in the island arc-field, or where the island arc-field overlaps the MORB-field. When the composition of the amphibolites only, so without the greenstones, dikes, and two-pyroxene gabbro, are plotted on a TiO_2 vs Y diagram (Perfit, 1980) the analyses show a trend similar to that of E-type MORB.

Thirteen samples were analyzed by neutron activation for rare earth elements (M.I.T. laboratory, Ila and Frey, 1984). Overall the chondrite-normalized patterns for the various Bermeja rock types are similar (Fig.3). Enrichment above chondrite ranges from 6 to 20 times, with flat, slightly LREE depleted patterns. These patterns are compatible with both those of N-type MORB (Basaltic Volcanic Study Project, 1981), and island arc tholeiites (Jakes and Gill, 1970). However within this group the field of foliated amphibolites of the Las Palmas area are distinctly more enriched in REE than the other rocks (Fig.3). The gneissic texture and the higher REE content may suggest an origin near a transform fault (Langmuir and Bender, 1984), this is supported by the occurrence of gneissic amphibolites, dredged from the deepest part of the VEMA Fracture Zone (Honorez and others,1984).

Clinopyroxene discrimination

Leterrier and others (1982) have shown that calcic pyroxene compositions in rocks that have only undergone low-grade metamorphism can discriminate between various tectonic

Table 2: Anhydrous analyses Bermeja Complex

	VP1	VP-3	VP-4	VP-2	VP-66	VP-78	EC-14	VP-79	VP-80	VP-85	EC-13	VP-179	VP-180
SiO2	50.43	45.45	49.46	51.29	51.28	47.77	47.17	40.63	50.11	50.09	50.31	48.11	49.52
TiO2	1.96	2.19	2.37	1.42	1.86	1.43	1.25	1.3	1.45	1.75	1.23	1.45	1.03
Al2O3	12.90	11.89	12.37	14.35	14.18	12.92	10.57	11.82	14.18	13.76	12.80	16.02	14.72
FeO*	14.00	15.94	16.24	10.64	13.02	12.30	10.3	11.37	10.91	12.87	11.82	9.67	9.67
MnO	0.25	0.23	0.23	0.18	0.2	0.22	0.18	0.21	0.18	0.20	0.20	0.15	0.16
MgO	7.70	10.34	6.76	8.29	7.25	13.27	12.29	26.12	8.52	7.48	12.04	8.46	9.35
CaO	9.72	11.81	9.55	10.28	8.03	8.90	17.29	7.71	10.72	10.01	7.19	13.49	8.59
Na2O	2.63	1.59	2.53	3.05	3.47	2.76	0.6	0.63	3.57	3.47	4.02	2.47	6.74
K2O	0.15	0.32	0.10	0.33	0.49	0.24	0.08	0.08	0.19	0.18	0.23	0.23	0.22
P2O5	0.25	0.24	0.38	0.16	0.23	0.19	0.26	0.13	0.17	0.19	0.15	ND	ND
Total	99.99	100.00	99.99	99.99	100.01	100.00	99.99	100.00	100.00	100.00	99.99	100.05	100.00
Sc	45	57	47	39	ND	ND	41	ND	ND	ND	37	ND	ND
V	448	507	543	294	401	343	185	304	317	395	179	326	244
Cr	168	227	134	221	162	116	129	150	206	140	159	199	316
Ni	53	70	44	57	75	63	64	85	65	38	60	61	102
Cu	7	62	46	70	46	65	<1(	58	62	48	29	78	89
Zn	123	102	94	89	83	76	59	67	72	62	84	61	65
Rb	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<3	<3
Sr	110	89	93	180	338	451	59	28	275	1016	89	364	779
Y	29	28	36	22	26	24	19	21	22	25	16	24	20
Zr	112	74	199	77	122	113	58	64	88	156	59	76	115
Nb	6	5	8	3	0	0	9	8	2	<	11	4	<2
Ba	150	153	167	783	368	132	269	235	985	650	179	179	179
La	4.97	3.08	7.75	2.77	3.38	2.83	<10	2.79	2.58	2.87	2.57	1.89	2.80
Ce	17.90	13.60	27.50	9.80	13.00	10.00	40.00	10.70	9.10	10.70	9.30	9.70	8.70
Nd	13.70	12.40	20.30	7.20	10.60	8.50	ND	8.30	7.50	8.90	7.90	7.20	7.20
Sm	5.02	4.63	6.59	2.91	3.76	3.08	ND	2.84	2.91	3.32	2.86	2.80	2.40
Eu	1.65	1.66	2.02	1.07	1.34	1.08	ND	1.08	1.06	1.19	0.98	1.05	0.91
Tb	1.06	1.10	1.65	0.86	0.88	0.79	ND	0.61	0.66	0.77	0.61	0.69	0.62
Yb	5.10	5.25	6.69	2.87	3.77	3.28	ND	2.89	3.10	3.58	2.94	2.75	2.35
Lu	0.73	0.76	0.98	0.41	0.55	0.47	ND	0.43	0.44	0.53	0.42	0.42	0.37
Hf	3.80	2.70	5.10	2.00	2.80	2.40	ND	2.00	2.10	2.40	1.90	1.37	1.65
Th	ND	ND	ND	0.20	ND	ND	ND	ND	ND	NC	0.10	ND	ND

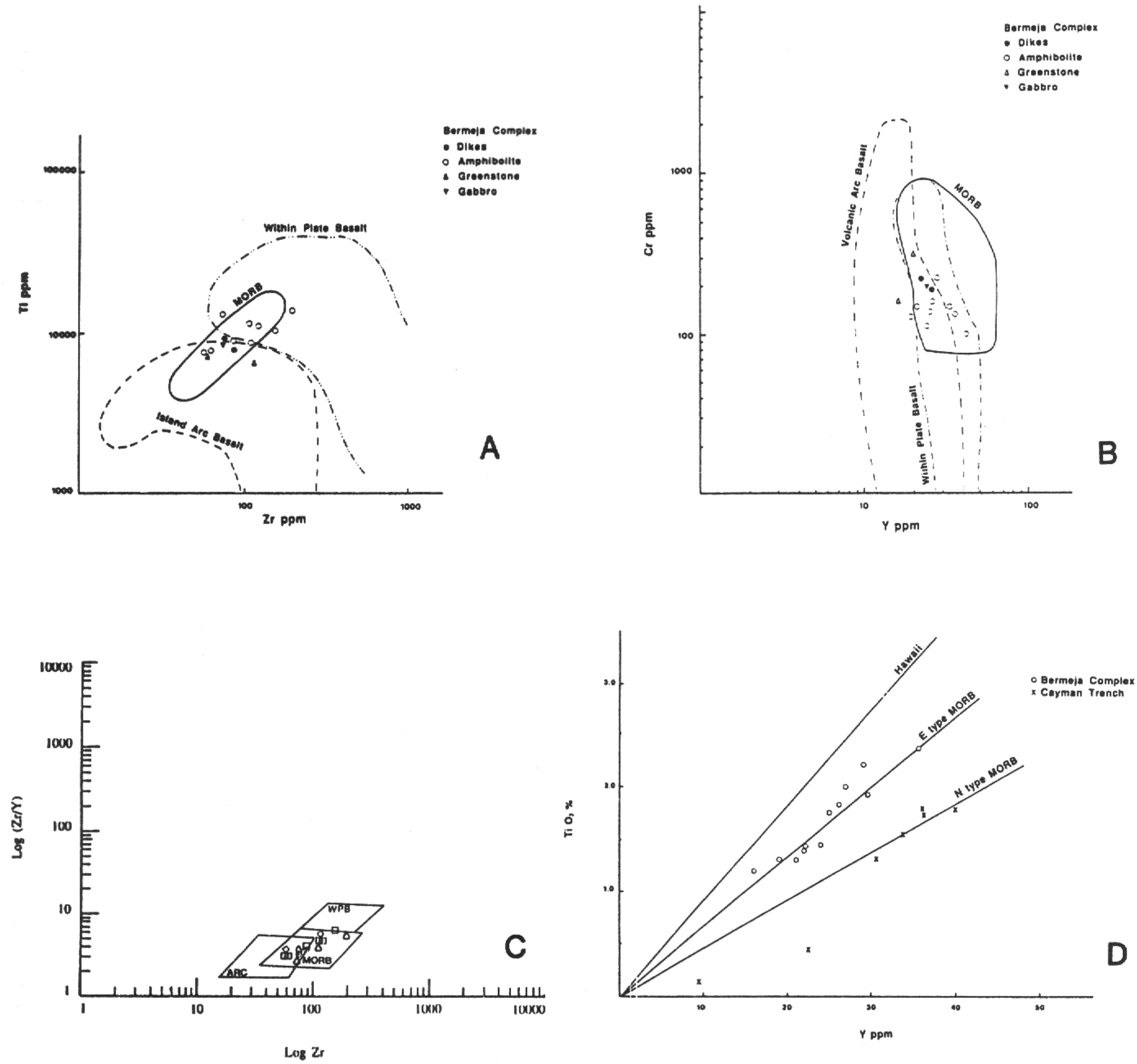

Fig.2: Chemical variation diagrams: 2A and B: Pearce (1982); 2C Pearce and Norry (1979); 2D: Perfit and others (1980).

environments. Calcic clinopyroxenes are preserved in a number of rock types in the Bermeja Complex. The metamorphic grade of these rocks ranges from very low (prehnite and chlorite), through low (chlorite, actinolite and albite), to medium (green hornblende and Ca- plagioclase). Clinopyroxene compositions were determined using a microprobe (Jeol Superprobe, Cornell University). The clinopyroxene relics from the amphibolites in Media Quijada, and Cerro Las Mesas do not give balanced analyses, indicating that the composition of the clinopyroxene has been affected by metamorphic processes. Analyses from pyroxenes of rocks with lower metamorphic grades (Table 4), the two pyroxene (VP179) gabbro breccia, the greenstones (VP259), and the meta-basaltic dikes (VP117), were plotted on the diagrams of Leterrier and others (1982). These plots suggest the host rocks were originally tholeiitic island arc basalts (Fig 4), a conclusion not contradicted by the whole rock chemistry.

MARIQUITA CHERT

The Mariquita Chert (Mattson, 1973) is a fine-grained greenish-gray or black radiolarian bearing rock, consisting of fine recrystallized quartz with minor iron oxides. It was named after Cerro Mariquita, the highest peak of the Sierra Bermeja, where it overlies the serpentinite. Other

Table 3: Anhydrous analyses Maguayo Volcanic Center

	VP114	VP-113	VP-112	VP-110	VP-120	VP-119	VP-105	VP-122	VP-124	EC-15	VP-118	EC-11	EC-12
SiO2	56.50	53.65	60.14	59.74	54.95	55.05	59.79	54.53	58.85	56.79	62.44	57.14	57.89
TiO2	0.98	0.88	0.96	1.16	1.34	1.17	0.82	1.39	0.90	0.70	0.69	0.76	0.77
Al2O3	17.85	16.87	18.14	16.93	17.24	17.59	16.12	16.75	16.57	16.72	17.16	16.99	16.58
FeO*	6.51	8.47	4.83	4.74	8.17	8.29	6.13	9.01	6.39	6.83	4.52	6.16	6.82
MnO	0.16	0.16	0.19	0.31	0.15	0.12	0.14	0.32	0.25	0.11	0.18	0.23	0.15
MgO	3.56	6.64	1.01	1.95	4.93	4.10	4.55	6.06	5.46	5.38	4.05	4.89	3.90
CaO	6.70	8.99	7.84	8.27	7.91	8.69	4.49	7.48	3.82	6.28	4.27	7.71	6.93
Na2O	4.79	2.62	4.78	5.81	2.85	3.00	5.29	3.63	4.21	4.31	3.87	3.37	3.35
K2O	2.59	1.38	1.64	0.61	2.05	1.56	2.40	0.54	3.33	2.62	2.54	2.45	3.30
P2O5	0.35	0.35	0.46	0.48	0.40	0.42	0.27	0.29	0.23	0.28	0.28	0.31	0.30
Total	99.99	100.01	99.99	100.00	99.99	99.99	100.00	100.00	100.01	100.02	100.00	100.01	99.99
V	189	174	175	207	253	226	142	268	157	114	117	107	110
Cr	236	232	21	0	23	51	55	18	20	170	35	91	105
Ni	57	92	3	8	13	14	29	13	23	59	13	24	20
Cu	57	55	38	177	50	8	21	77	26	0	28	0	0
Zn	86	60	80	72	81	78	68	74	73	69	116	77	58
Rb	33	17	27	1	24	1999	33	4	53	48	53	47	79
Sr	580	543	585	511	448	554	599	670	569	498	489	506	548
Y	18	17	17	18	19	18	16	16	18	16	17	15	23
Zr	182	171	176	246	185	166	161	168	149	140	153	143	159
Nb	12	0	10	30	19	15	13	1	11	14	24	17	16
Ba	1091	591	834	584	1155	883	976	1292	1579	1075	1410	717	806
La	14.00	19.90	30	37	24	19	27	21.50	23	25	13	28	19
Ce	88.00	43.10	68	70	93	68	78	45.00	110	93	91	75	91
Nd	ND	21.40	ND	ND	ND	ND	ND	21.60	ND	ND	ND	ND	ND
Sm	ND	4.13	ND	ND	ND	ND	ND	4.60	ND	ND	ND	ND	ND
Eu	ND	1.20	ND	ND	ND	ND	ND	1.38	ND	ND	ND	ND	ND
Tb	ND	0.46	ND	ND	ND	ND	ND	0.59	ND	ND	ND	ND	ND
Yb	ND	1.68	ND	ND	ND	ND	ND	1.68	ND	ND	ND	ND	ND
Lu	ND	0.26	ND	ND	ND	ND	ND	0.26	ND	ND	ND	ND	ND
Hf	ND	3.49	ND	ND	ND	ND	ND	3.18	ND	ND	ND	ND	ND
Th	ND	3.40	ND	ND	ND	ND	ND	3.40	ND	ND	ND	ND	ND

Table 4: Representative analyses clinopyroxenes, Bermeja Complex

	Hornblende -Two pyroxene Gabbro (VP179)				Dikes (VP117)				Greenstones (VP259)		
sample # mineral#	179-1	179-2	179-3	117-1 core	117-1 rim	117-2.3	117-7.2	259-1 core	259-1 rim	259-3 core	259-5 rim
SiO2	52.01	52.18	51.25	53.43	51.52	52.74	52.82	52.46	51.89	52.95	51.81
CaO	21.00	19.58	21.06	19.73	19.20	20.24	21.00	20.86	19.96	20.12	20.63
Al2O3	1.11	1.57	1.64	1.80	3.05	1.98	2.02	2.14	2.93	2.21	3.36
FeO	10.28	12.33	11.59	5.53	5.89	5.81	5.57	5.00	7.67	5.31	6.47
K2O	0.00	0.00	0.01	0.02	0.02	0.01	0.00	0.03	0.02	0.00	0.00
MgO	13.44	13.35	12.99	17.26	16.71	17.23	17.06	17.93	16.48	18.01	16.90
Cr2O5	0.08	0.00	0.01	0.19	0.27	0.17	0.16	0.27	0.03	0.21	0.02
Na2O	0.32	0.30	0.29	0.24	0.26	0.26	0.22	0.25	0.26	0.25	0.28
TiO2	0.16	0.25	0.34	0.19	0.28	0.19	0.24	0.28	0.56	0.28	0.55
MnO	0.34	0.33	0.29	0.09	0.09	0.11	0.12	0.14	0.22	0.15	0.14
Oxygen			0.00					0.00	0.00	0.00	0.00
TOTAL	98.74	99.89	99.47	98.48	97.29	98.74	99.21	99.36	100.02	99.49	100.16
cpx structure based on 6 O											
Si	1.9746	1.9656	1.9452	1.9743	1.9331	1.9515	1.9485	1.9299	1.9143	1.9410	1.9011
AlIV	0.0254	0.0344	0.0548	0.0258	0.0669	0.0485	0.0516	0.0701	0.0858	0.0591	0.0989
AlVI	0.0244	0.0354	0.0185	0.0528	0.0680	0.0377	0.0363	0.0229	0.0416	0.0363	0.0466
Ti	0.0044	0.0072	0.0098	0.0053	0.0079	0.0053	0.0065	0.0077	0.0155	0.0077	0.0151
Fe	0.3263	0.3884	0.3678	0.1709	0.1849	0.1798	0.1717	0.1540	0.2367	0.1626	0.1986
Cr	0.0023	0.0000	0.0004	0.0055	0.0079	0.0051	0.0047	0.0078	0.0008	0.0060	0.0006
Mg	0.7605	0.7496	0.7352	0.9510	0.9346	0.9503	0.9380	0.9834	0.9062	0.9841	0.9247
Mn	0.0109	0.0106	0.0094	0.0028	0.0028	0.0034	0.0038	0.0045	0.0068	0.4700	0.0043
Ca	0.8541	0.7903	0.8563	0.7812	0.7717	0.8064	0.8298	0.8221	0.7891	0.7902	0.8108
Na	0.0240	0.0216	0.0211	0.0170	0.0187	0.0187	0.0160	0.0178	0.0183	0.0181	0.0199
K	0.0000	0.0000	0.0003	0.0010	0.0009	0.0003	0.0000	0.0013	0.0008	0.0001	0.0000
O	6.0000	6.0000	6.0000	6.0000	6.0000	6.0000	6.0000	6.0000	6.0000	6.0000	6.0000

chert occurrences mapped originally as Mariquita chert are at Punta Melones (El Combate), Media Quijada, and San German (Krushensky and Monroe, 1979, Volckmann, 1984a,b,c).

Based on radiolarian chronostratigraphy (Mattson and Pessagno, 1974, 1979, Pessagno written comm. in Volckmann, 1984c, Schellekens and others, 1989, Montgomery, this volume)

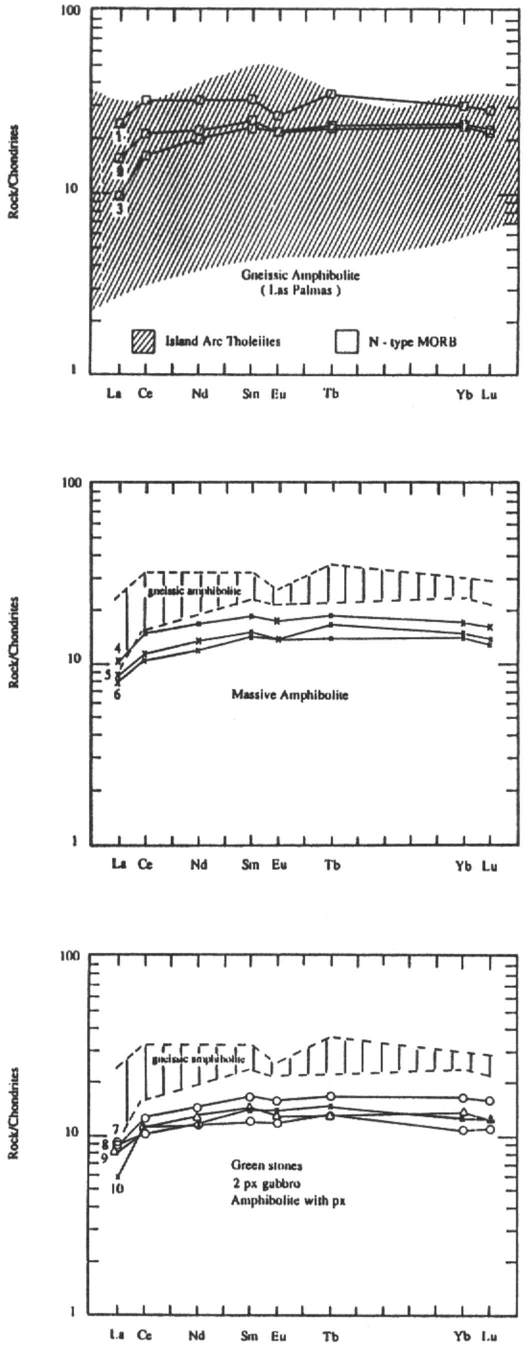

Fig.3: Chondrite normalized REE patterns for rocks of the Bermeja Complex. Normalization values from Nakamura (1974). 1:VP4; 2:VP1; 3:VP3; 4:VP66; 5:VP78; 6:VP80; 7:VP85; 8:EC13; 9:VP117; 10:VP179

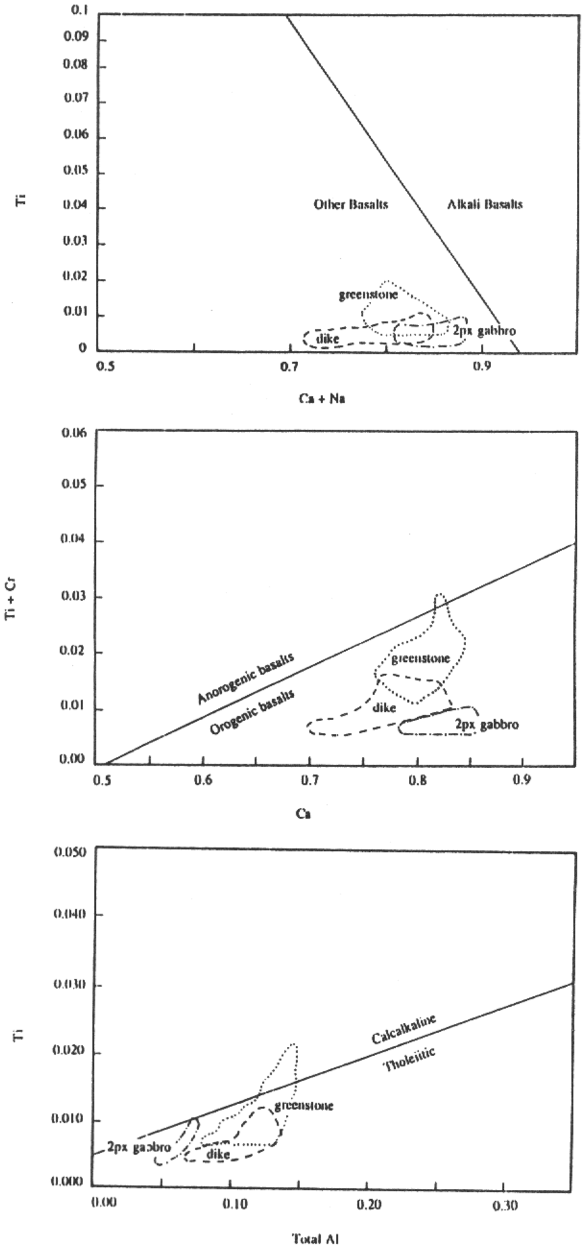

Fig.4: Clinopyroxene discrimination diagrams after Leterrier and others (1982). greenstones: Las Mesas Greenstone, (VP-259); dikes: metabasaltic dikes in amphibolite near Bo. Las Palmas (VP-2, VP-117); 2px gabbro: amphibole two pyroxene gabbro near Maricao (VP-179).

three chert forming episodes can be distinguished (Fig.5).

Kimmeridgian to Tithonian radiolarian chert in central northern Sierra Bermeja was interpreted as having been deposited in an abyssal depositional environment, at northern Tethyan paleolatitudes (approx. 22 - 30°N). A second sequence of chert from the southern Sierra Bermeja of Hauterivian to lower Albian age, suggests they were deposited in a bathyal environment. Mattson and Pessagno (1979) described radiolarians of this age from cherts that are intercalated with volcanic sandstones.

A third period of chert formation occurred in the Upper Cretaceous. Cenomanian radiolarian cherts overly a serpentinite conglomerate in Media Quijada; Campanian chert overlies the

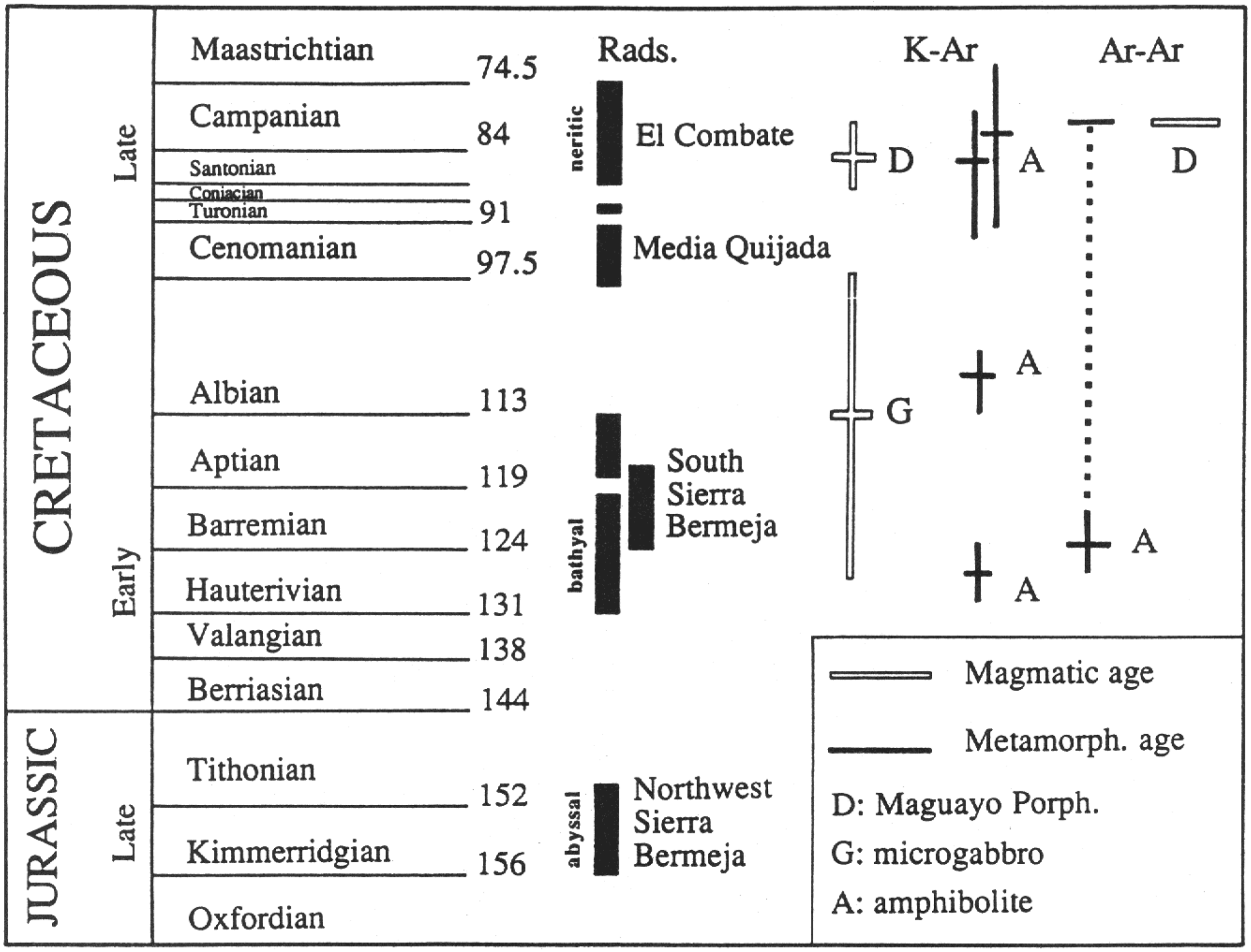

Fig.5: Radiolarian chronostratigraphy and radiometric age dates for SW Puerto Rico. Data from Mattson (1964), Tobisch (1968), Cox and others (1976), Mattson and Pessagno (1979), Schellekens and others (1989), Montgomery (this volume) and Schellekens (unpublished).

serpentinite near El Combate (Schellekens and others, 1989, Montgomery, this volume; Turonian chert is found near San German (Pessagno writ. comm.in Volckmann, 1984c).

MAGUAYO VOLCANIC CENTER

In southwest Puerto Rico, north and south of the Valle de Lajas, a sequence of volcanic rocks unconformably overlies the Bermeja Complex. North of the Valle de Lajas, the volcanic rocks are mapped as Boqueron Basalt and Lajas Formation, and are overlain disconformably and locally conformably by the Cotui Limestone (Volckmann, 1984 a,c,d). South of the valley the volcanic rocks are mapped as basaltic andesite (Kba) by Volckmann (1984b) and as augite-hypersthene andesite, augite andesite, and augite-hornblende andesite by Almy (1965). These are overlain by the Parguera Limestone (Almy, 1965, 1969, Volckmann, 1984b). The Cotui Limestone, the base of which is of Campanian age (Santos and Kauffman, 1989), transgressively overlies the northern volcanic sequence. The age of the Parguera Limestone is also reported as lower Campanian (Almy, 1965, 1969) suggesting that these two limestone formations are correlatable. As no radiometric ages for the volcanic rocks are available, their minimum age can only be assigned as at least lower Campanian. Based on the stratigraphic position of these volcanic rocks, and their similar petrographical, and geochemical characteristics, the northern and southern volcanic sequences are tentatively correlated.

The name Maguayo Volcanic Center was given for the Maguayo Porphyry stock. This stock, based on its geochemistry, its radiometric ages (K-Ar age of 86.1 $\pm$ 2.1 Ma, Cox and others, 1977, Ar-Ar age of 83 Ma, Schellekens, unpublished), and its central geographic position with respect to the volcanics, probably represents the volcanic

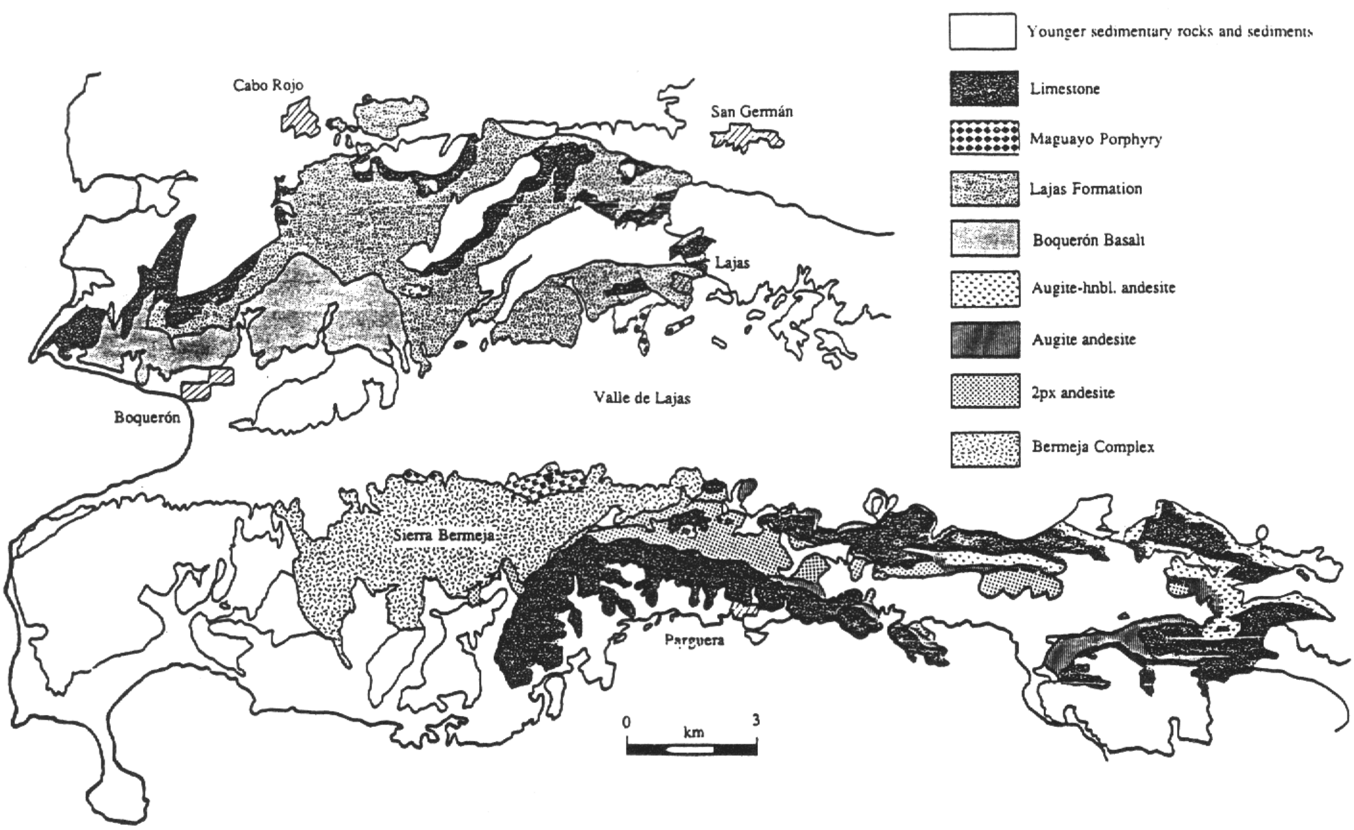

Fig.6: Geologic map of southwest Puerto Rico (see inset fig. 1 for location) showing outcrop areas of rocks assigned to Maguayo Volcanic Center (Redrawn after Almy, 1965, and Volckmann, 1984abc).

complex from which these volcanics were erupted. The Maguayo Porphyry of dacitic composition (Mattson, 1973, p.23), intrudes amphibolites and serpentinites of the northern end of the Sierra Bermeja. It consists of feldspar and hornblende, rare biotite, and quartz phenocrysts in a felsic groundmass. Rocks correlated with the Maguayo Porphyry also occur as dikes and sills cutting the Cajul Volcanics and the Mariquita Cherts. Dikes and small intrusions north of the Valle de Lajas have also been tentatively correlated with the Maguayo Porphyry. Volckmann (1984c) suggests that part of the Valle de Lajas may be underlain by this intrusion.

Geochemistry

Thirteen new whole rock analyses were obtained for rocks considered to belong to the Maguayo Volcanic Center (Table 3). Geochemically the rocks range in composition from basaltic andesite to dacite. All major elements and many trace elements show evidence, on geochemical diagrams, of element mobility (Wood and others, 1976). Those trace elements, that suggest that they behaved on a refractory manner include Sr, Y, and Zr. Spider plots of rocks, normalized to primordial mantle, for the Maguayo Porphyry and related volcanic rocks, all show a similar pattern. In order to facilitate comparison between the different units, the band of compositions for the entire Volcanic Center is drawn on the diagrams for the individual mapped formations (Fig. 7). REE patterns for the Boqueron Basalt and the rocks of the Lajas Formation, are almost identical, and show a LREE enriched pattern characteristic of calc-alkaline volcanics (Fig. 8).

AGES

Radiometric and fossil age determinations are summarized in figure 6. The oldest radiometric age of 126 $\pm$ 3 Ma (K-Ar date on hornblende in the amphibolites of the NE Sierra Bermeja, Cox and others, 1977) is interpreted as a metamorphic age. The other ages for the amphibolites, 110 $\pm$ 3.3 Ma (Mattson, 1964), and 86.3 $\pm$ 8.6, and 84.9 $\pm$ 8.5 Ma (Tobisch, 1968) are all considered to be reset, possibly by the intrusion of the Maguayo Porphyry dated at 86.1 $\pm$ 2.1 Ma (K-Ar: Cox and others, 1977), and 83 Ma (Ar-Ar: Schellekens, unpubl.). Based on the reinterpretation of the hornblende in the two-pyroxene gabbro near Maricao as a late-magmatic mineral, the 112 $\pm$ 15 Ma K-Ar (Cox and others,

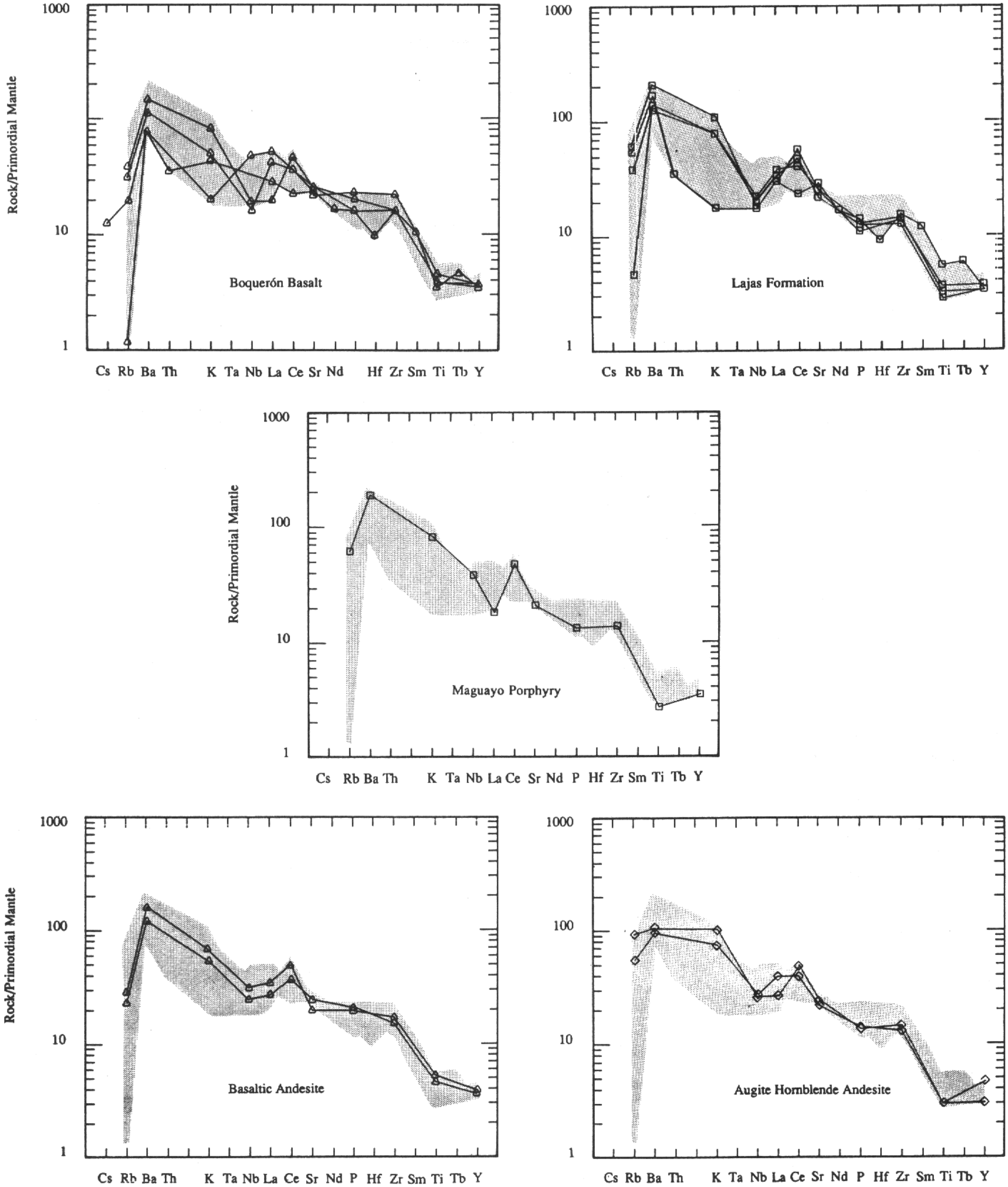

Fig.7: Primordial mantle normalized spider plots of Maguayo Volcanic Center rocks (after Wood and others, 1979). To facilitate comparison the boundaries of the entire field of Maguayo Volcanic Center rocks are drawn on each separate diagram. NB. Not all trace elements were analyzed for all samples.

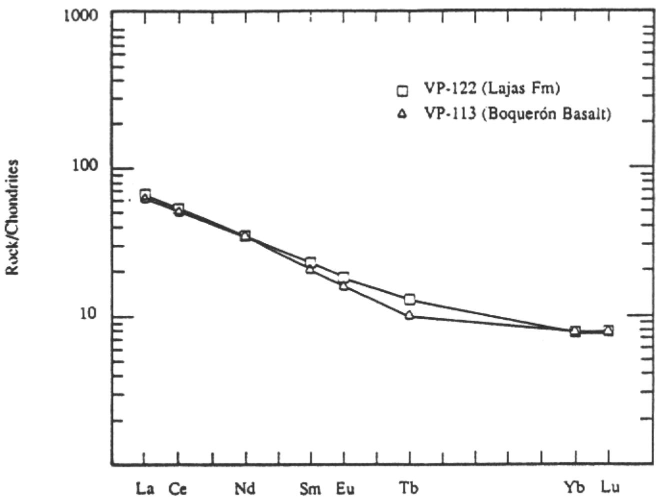

Fig.8: Chondrite normalized REE patterns for rocks of the Maguayo Volcanic Center. Normalization values from Nakamura (1974).

1977) is reinterpreted as a magmatic age. The massive amphibolite of Cerro Las Mesas was dated by Ar-Ar at 123.1 ± 2.6 Ma, with a second plateau age of 80 Ma (Schellekens, unpublished). This younger age presumably represents the age of the retrograde greenschist metamorphism of the amphibolites.

CONCLUSIONS

The formation of the rocks from southwest Puerto Rico can be divided into three stages (Fig. 9):

A first stage, characterized by Late Jurassic (156 - 146 Ma) abyssal chert deposition, is interpreted to have occurred at northern Tethyan latitudes. This conclusion is compatible with the paleomagnetic data for the Colombian Basin (Ghosh and Hall, 1989). The ocean floor on which these cherts were deposited may be present in the

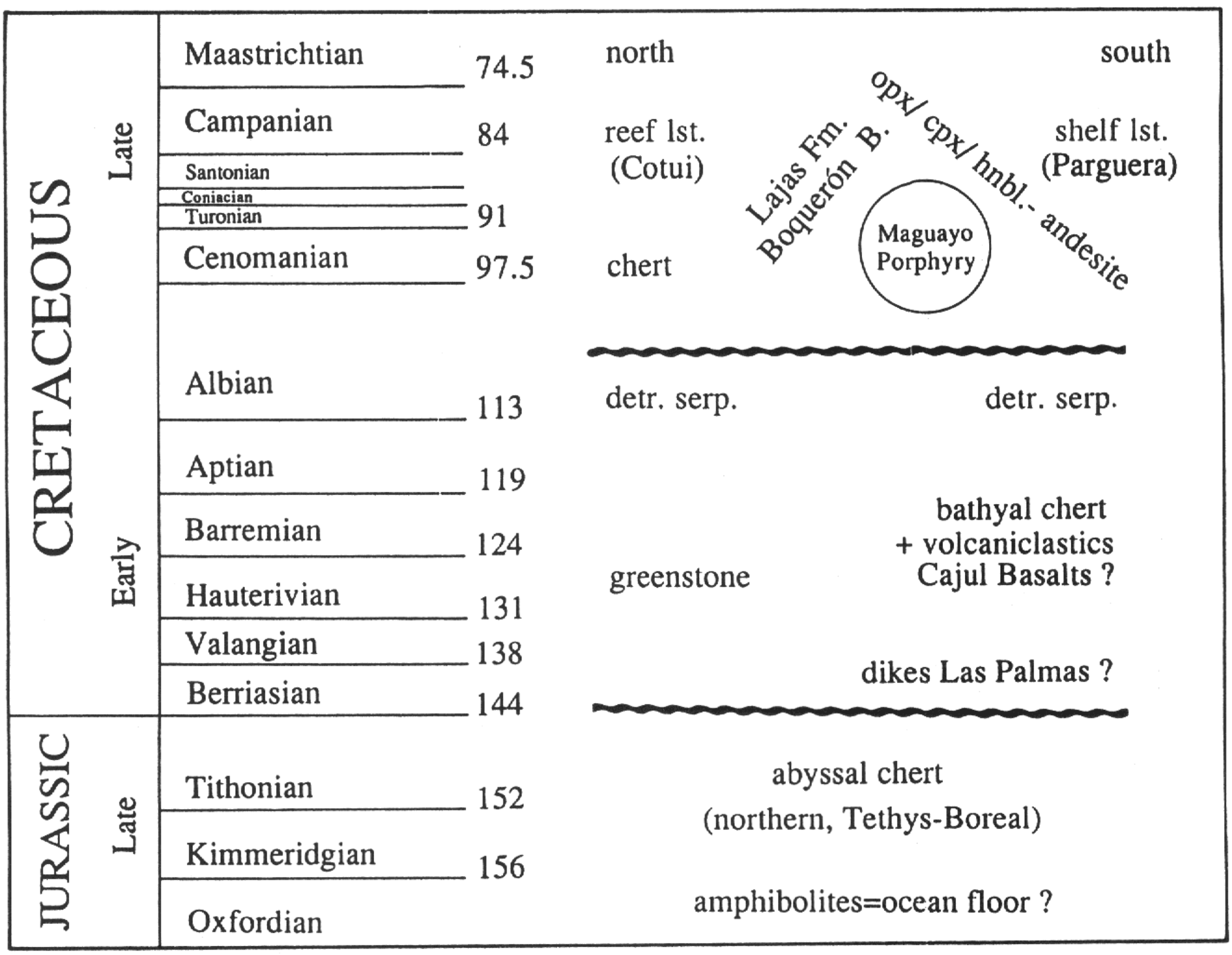

Fig.9: Summary of the stratigraphy of southwest Puerto Rico.

Bermeja Complex, as the amphibolites showing oceanic heritage.

The second stage is represented by cherts containing intercalated volcanic-derived material, that were deposited in a bathyal environment, during the Hauterivian to early Albian (131 - 113 Ma). Other rocks of this stage are amphibolites from both the northern and southern serpentinite belts, which give metamorphic radiometric ages of 123 and 126 Ma respectively, and the microgabbro from Maricao with an age of 112 Ma. The amphibolites of the northern belt are associated with the Las Mesas Greenstones, both have undergone greenschist metamorphism, presumably at around 80 Ma. Geochemical evidence indicates that the greenstones and the microgabbro represent island arc magmatic rocks. Other rocks with an island arc signature occur as low grade metamorphosed dikes, cutting the amphibolites of the southern belt.

The third stage is represented by the Maguayo Volcanic Center, an island arc volcanic complex of pre-Lower Campanian age, that intrudes and overlies the Bermeja Complex. This volcanic center was flanked by a carbonate platform to the (present day) north (Cotui Limestone), and a reef, carbonate shelf, slope to basinal environment to the (present day) south (Parguera Limestone).

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